A PHYSICIST DISTANCE RUNNER

A Definitive Guide to Running Efficiently, Faster and Farther

By Andrew W. Chow

Athletic performance depends to a large degree on natural ability, skills, strength, and endurance, and the basic attributes of a naturally gifted athlete can not be overstated. On the other hand for the mass of ordinary people lacking in coordination and stamina, just to perform at a level of minimal acceptability often requires a significant degree of dedication and hard work. Rather than just do what comes naturally, those of us with lesser talents must commit to first understanding requirements and techniques before finally training our bodies to do what we think is right. The need to understand how and why has led to A Physicist Distance Runner.

PART 1 – RUNNING AND WALKING

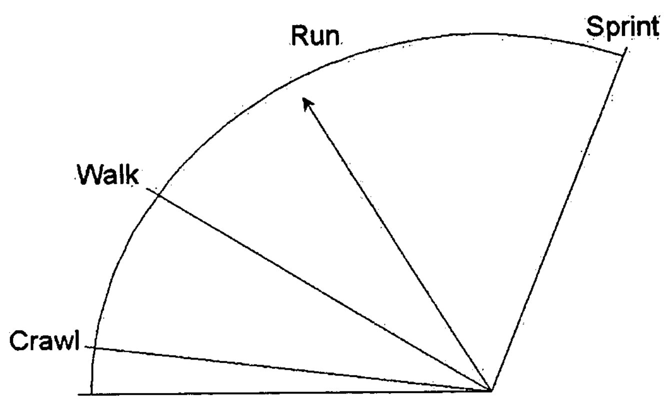
A Baby's First Step

A baby first learns mobility by crawling. Rising on hands and knees offers stability with four support points, but movement is slow. If we were four-legged beasts, babies would have to learn as a next step how to trot and to gallop, but we are not animals and can balance our bodies on two feet. So, as a baby develops coordination and manages to stand up, walking becomes the norm with movement more superior and natural to the human skeletal structure. Carrying to the next step of development, the baby learns how to run, and all out is the way to go, sprinting as fast as possible.

Indeed we do sprint, with performance of just about every sport predicated on maximum running speed: a football half back or wide receiver running down field, a baseball runner between the bases, basketball fast break, a soccer player chasing the ball, and the list goes on. Even in track and field, reductions in speed for the intermediate distances only ratchet down the maximum speed somewhat, and certainly not into the velocity range of walking.

The diagram below pictorially depicts the forgoing discussion, in the form of a pace meter.

PACE METER



We take quantum steps to advance from crawling to walking and then to sprinting. Most runners do not have the skills and are not naturally trained to vary running speed like turning up a rheostat, or a radio volume dial. For long distance running most runners tend to pull back from the speed and physical motion of a sprinter in a hit and miss fashion until a sustainable long-term pace is found, rather than turning up the effort from a walk to a run and then increasing the speed thereafter. To the extent an average long-distance runner can master running speed increases from the direction of walking and with a style derived and evolved from the walking form, the ultimate sustainable speed is likely to be faster than learning how to run slowly after mastering the fine points of sprinting.

Sprinting Motion

Running speed is a product of stride rate and stride length. Stride rate is a function of how fast a runner can turn over the feet. Stride length comprises two components, ground distance and air distance. Ground distance measures the distance traveled by a runner while one foot remains on the ground, and it is limited by the runner's leg length and how far the leg can kick back in each step. By trigonometry, ground distance of each step is about leg length times the sine of the angle the back leg makes with the vertical position – in other words, the distance on the ground from directly under the body to the tip of the back-stretched leg.

Since ground distance is limited and in order to maximize speed, a good sprinter must attain the greatest air distance possible, meaning the back leg must kick with a force sufficient to lift body and both feet off the ground. Thus with each stride, the back leg has to exert a force with a vertical component greater than body weight to achieve lift off. By trigonometry, total leg force has to exceed body weight divided by cosine of the leg angle. Such lift-off force requires power and strength, and that is why sprinters are muscular. Upon landing, total leg force is actually lower than at the back of a stride at lift off because the leg is now directly under the body without trigonometry angle effect.

Only the best runners can cover an entire marathon with strides that have both ground distance and air distance. As a ball park estimate, a marathon pace of perhaps seven minutes or faster would be compatible with strides that encompass both ground and air distances, sailing from one step to the next. For ordinary runners, marathons are run largely with ground distances only, with one foot always on the ground. All the proof we need is to look at pictures taken at marathons and see how many photos show ordinary runners without a foot in contact with the pavement.

Walking Motion

Walking motion consists entirely of ground distances, planting one foot on the ground before lifting the back leg forward for the next step. Without air distance, there is no need to over exert the back leg to achieve lift-off. As a matter of fact, the legs primary function is to support body weight, just rolling the body along. Imagine a situation where a walker can take very tiny steps in rapid succession; the limiting case of such leg movement would imitate the effects of a wheel, keeping a supported object at a fixed distance above ground. In terms of text required for discussion, walking is covered in just this paragraph, in contrast to a more tedious discussion on the sprinting motion. In practice, walking motion is equally simplistic and easy to execute, but more importantly it is superior and accords a higher level of efficiency without lift off.

Finding Optimal Running Pace

The implication from the foregoing discussion is huge on how a long-distance runner finds a sustainable running pace, whether derived from turning down a sprinting motion or achieved through cranking up the walking rhythm, which is inherently more efficient. Unfortunately, most of us learned slow running from slowing the sprint, still kicking the back leg with every stride as if to achieve lift off although not leaving the ground at all. Many runners have difficulties eliminating the "fathom" liftoff that zaps energy, and it shows in the body up and down motion. It takes concentration, effort, and practice to limit the back leg's force at full extension, a key to distance running efficiency.

PART TWO – ARM SWING AND RUNNING

Discussion of how nature behaves is inherent to A Physicist Distance Runner. A person with basic knowledge of physics would readily understand the rationale used to support the improved approach described here for running better and faster. However, readers not accustomed to some of the technicalities are assured that physical models can be constructed to demonstrate the validity of the physics presented.

Isaac Newton's Apple

If a person holds out an apple at arm's length, is work being done? Well, both yes and no answers are "correct". Clearly the yes answer is supported by the fact that the arm gets tired over time, and the farther out the arm is extended, the more difficult it is to hold the apple for a long time. On the other hand for the no answer, if Isaac Newton's apple stayed on the tree and never fell off, it would be hard to say that the tree did any work at all by simply keeping the apple's stem attached to a branch.

From physics work is released when the apple falls from the tree, releasing gravitational potential energy and converting it into kinetic energy. If the hand-held apple is tossed up and then caught on its way down, work is done to throw the apple up against gravity, but the kinetic energy released at falling is lost. Our hands and arms do not behave like pogo sticks with the ability of storing kinetic energy in spring-like fashion for subsequent release. The same is true with our legs with every stride we take. We can run in place all day long and not go anywhere; yet we would still be expending substantial energy bouncing up and down, just like repeatedly tossing an apple up into the air.

Running in place has the elements of the previously described Pace Meter sprint form, with a combination of ground time and air time that is characterized by both feet off the ground. Again the legs must apply forces greater than body weight to achieve lift off. When both feet are off the ground, the body behaves exactly like the earlier described tossed apple, consuming energy with every bounce. Now consider what it would be like to walk in place with 100% ground time, with at least one foot always on the pavement. After trying walking in place in comparison, the efficiency of the walking motion is clear, and it should be obvious that we ought to find an optimal running pace by increasing the walk rhythm, with a form evolved from walking, rather than slowing down the sprint.

The Necessity of Arm Swing

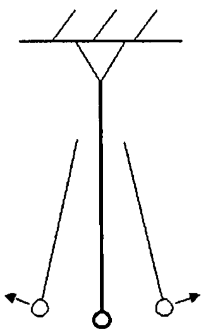
As a simple exercise to demonstrate physical body movement, stand on one leg with both arms down on the side and without any arm motion, swing the other leg back and forth. The resultant movement is awkward with body twist and torque applied on the floor. The effects of this exercise are more pronounced if it were done with the planted leg raised to the ball of the foot, on a smaller point contact with the ground.

As a second part of this exercise, incorporate arm motion with the leg swing. Hold the leg on one side forward, and for the arms, hold the arm on the same side back and on the other side forward. Swinging both arms and leg simultaneously, and it should be obvious that the arm-balanced motion is smoother and easier to execute.

In actual running (or walking) bringing the back leg forward for the next stride creates an angular momentum around the foot planted on the ground, but the arm swing generates an offsetting angular momentum. Thus arm swing integral to every stride is important for form and function and must move in exactly the same rhythm as the legs.

Swinging Pendulum

The following diagram shows a pendulum hung from a fixed point, and it comprises a shaft and a mass at the end.

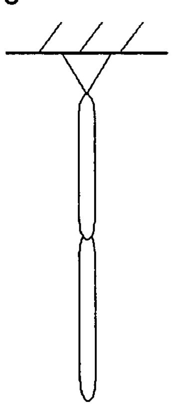


For the sake of discussion simplicity, assume as a base case that the entire weight of the system is concentrated at the point mass, and ignore the effects of friction. Moving the pendulum to either side from center requires work as the mass is moved up against gravity, and gravitational potential energy is stored with increasing displacement. When the pendulum is released, it falls and converts gravitation potential energy to kinetic energy. Pendulum speed increases until it reaches maximum velocity at center, then it slows until all kinetic energy is converted back into gravitational potential energy, at the same height at a full stop as when the pendulum was first released. In an idealized environment without friction, this process will repeat indefinitely.

Physicists describe the time it takes a pendulum to swing back and forth as the period (and conversely natural frequency) of oscillation. Without going into depths of physics, it can be shown by physical demonstration that a pendulum's frequency of oscillation depends on its shape and size. As it is not possible to demonstrate motion in this text, readers are asked to consider different clock pendulums, and it should be obvious that the smaller pendulum of a cuckoo clock swings with a higher frequency than the much larger pendulum of a grandfather clock. Furthermore, we make these clocks run faster by moving the pendulum weights up and slower by shifting the weights down, changing the natural period of oscillation via adjustments to the pendulums.

Walking Arm Swing Pendulum

This diagram schematically shows an upper and lower arm hung from a fixed point.

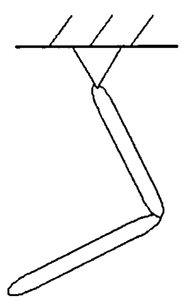


In the configuration shown, the fully extended arm behaves like the "grandfather clock" pendulum with a low frequency of oscillation that is suitable for slow walking. In line with the previously established tie between arm speed and leg speed, the number of walking steps taken in a given period of time is exactly the same as that of the swinging arm's oscillations.

While it is possible to apply physical force to actively push fully extended arms to swing faster or slower than their natural frequency, it requires effort to counteract the natural rhythm. In addition, the energy expended to modify the natural frequency is not fully recovered with each swing. So, if it were desirable to increase speed, it makes sense to change the configuration of the arms and thus the pendulums, in order to swing faster.

Running Arm Pendulum

We know naturally how to do that. When we need to increase running speed and thus the corresponding stride rate (the number of steps taken in a given amount of time), we bend our arms at the elbows for a higher frequency of oscillation, as shown in the next diagram.



For elite long-distance runner, the lower-arm is typically pulled up to less than 90 degrees. For lesser runners, especially after fatigue has set in, the arm opens up to much more than 90 degrees, thus slowing the natural frequency of oscillation to match the associated slower rhythm of the legs.

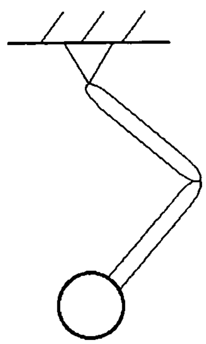
It should be noted in the above "center" at rest position, the center of gravity of the combined upper and lower arms hang directly beneath the shoulder, and in this state, the upper arm is pushed back. As efficient pendulum arm swing moves back and forth with the least amount of energy loss, experienced runners know to instinctively pull the arms back with each step, rather than push the arms forward.

We live in a world with friction and energy loss. To keep the arms swinging, a runner has to exert energy to move the arms. If the arms are pulled back, the gravitational potential energy that is stored would be recovered in the swing forward. On the other hand, if the arms are pushed forward, and assuming they are displaced too far, the gravitational potential energy from a frontal over-reach would be lost in the subsequent back swing on account of the limit of how far the arms could be swung back.

This effect should be obvious to anyone accustomed to seeing runners in motion, with the elbows thrown back in graceful strides. Seldom do we see hands pushed out in front, with the exception of sprinters coming out of starting blocks with face down, then the pendulum motion would support hands pushed all the way up to the forehead.

Distorted Motion with Hand Weights

Although a user of hand weights may develop gripping hands, stronger arms, and bulkier shoulders, any experienced athlete who has tried hand weights knows that weighted hands as shown in the center at rest position below make running or walking nearly impossible, or very awkward at best.



The difficulty in running or walking with hand weights stems from the following,

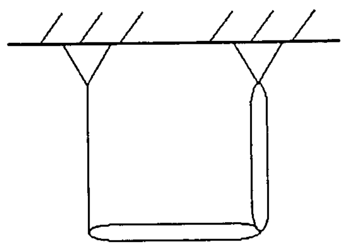
1) the added weights grossly distort the offsetting angular momentum between the arms and the legs,
2) the weights lower the arms' natural frequency of oscillation, thus forcing the legs to move at a correspondingly slower rhythm, and
3) resting at the center position the elbows of the weighted arms are pushed back with limited additional back swing potential, and this lack of rear swing movement results in a loss of pendulum motion and the associated recapture of gravitational potential energy. Without pendulum movement, arm swing comes about by actively and repeatedly throwing the weights upward and forward from the shoulders, in other words, from pumping iron.

Rather than looking at the detrimental effects hand weights have on running or walking and if we start from an initial condition with hand weights, taking the weights off would raise the natural frequency of arm swing and thus improve running speed. The question to ask then is how do we know our arms without weights would be the configuration most optimal for running or walking. If taking some weigh off improves performance, does it not follow then taking more weigh off would result in additional improvement? Indeed, the foregoing discussion in physics would support that notion posited here, but it would be extreme to cut off the hands just to be able to run faster.

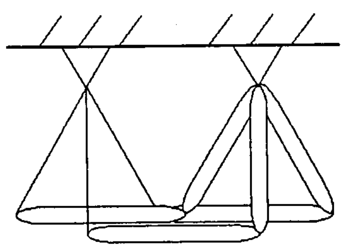
The above line of reasoning is a red herring that leads to a suggestion of cutting off the hand. However, it is indeed possible to raise the natural frequency of arm swing above that of the naturally bent arms. Approaching the optimization problem from a different perspective, and considering natural frequency has been increased from the walking straight arms to the bent running arms, it is obvious that man had instinctively adopted an improved arm configuration with a lower rotational inertia to achieve improved results without amputation. If we follow this route of rotational inertia reduction, we can gain further natural frequency improvement as race walkers have done with some success although with a higher degree of difficulty.

Faster Arm Swing

To increase the natural frequency of arm swing, consider the following arrangement whereby the hand is supported at rest by a tether about the length of the upper arm. The support of the tether is position so that the tether is about parallel with the upper arm so that the center at rest position of the arm is fully described by the following figure.



For readers not familiar with physics, a physical model of the tether-supported arm would show that it has a higher natural frequency of oscillation than the previously shown unsupported arm. The diagram below shows arm movement with the tether support.

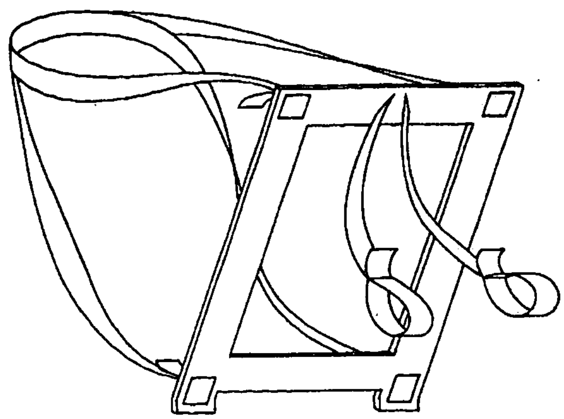


It is evident that with the elbow relaxed, the lower arm does not rotate. In essence, the tether permits a reduction of the rotational inertia of the arm, and with a lower inertia, the natural frequency is increased. While all of the discussion here could be supported by mathematics, the results should be intuitively obvious. Total kinetic energy at the center position comprises two components, movement of the center of mass and the arm's rotation, and releasing tethered-supported and unsupported arms with the same gravitational potential energy ought to have the same kinetic energy at center position. If both arms were to have the same natural frequency, they would have to have the same velocity at the center, at rest position, but that can not be the case. Because if they were to have the same velocity, the kinetic energy from the movement of the center of mass would be the same, but the supported arm would have less kinetic energy associated with arm rotation due to the fact that the lower arm does not rotate. Therefore, both arms can not have the same velocity, and in order for the maximum kinetic energy to be the same for both cases, the tethered arm has to have a greater velocity, thus a higher natural frequency of oscillation, a quicker rhythm.

PART THREE – AN INNOVATION FOR RUNNING FASTER

A Fast Arm-Swing Tether System

The following drawing shows a tether arm support system, comprising of 1) two tether loops for hand support, 2) a rigid frame that extends out in front of an athlete's chest, and 3) two tether straps worn around the athlete's neck. The straps hold frame bottom onto the chest and allow the top of the frame to protrude out to provide support for the tether loops. The drawing depicts the frame as viewed from 1 to 2 o'clock from in front of the athlete.



It should be obvious to any physicist that shortening the tethers on the loops would further increase the natural frequency over the previous diagram configuration with the lower arm shown parallel to the ground.

We bent our straight arms to shift from walking to running. The tether loops provide a means to further reduce the arms' rotational inertia, thus facilitate faster arm swings to allow man to run faster.

PART FOUR – IMPLICATIONS

Faster Ordinary Runners

As ordinary runners stay on the ground with strides consisting of exclusively ground distances, stride length limits the maximum speed that could be attained. The only way to increase overall running speed with one foot always on the ground is to increase the number of steps taken in a given amount of time. The tether support illustrated above accomplishes this goal, raising the natural frequency of the arms and thus the number of steps that can be taken on a sustained basis. The tether has additional benefits in reducing arm fatigue in comparison to having to hold arms up without support; furthermore with fatigue in the unsupported case, elbow angle opens up and slows running rhythm which would never happen with the tether support.

More Efficient Ordinary Runners

If the strap support is used without any desire to increase speed, it will increase running efficiency and reduce effort. Using it to run at the same speed, the distance covered by each stride is reduced, meaning a smaller leg angle. In order words, the runner can reduce the maximum leg force by way of trigonometric cosine effect of a smaller angle, and the result is one notch closer toward the limiting case of imitating a wheel.

Faster Olympic/Elite Runners

Super athletes run with strides having both ground and air distances. Using the tether support and assuming the same running speed is maintained, the tethered arms would swing with a higher natural frequency; therefore a greater number of steps are taken over the same distance in the same amount of time. With each stride's ground distance largely fixed, that means the elite runner would spend a greater proportion of the run with one foot on the ground and thus maximizing total ground distance. At the same time, the offset is that less distance is covered while gliding through the air, and the amount of time spent air borne is reduced. Thus the tether facilitates a reduction in energy loss associated with tossing Isaac Newton's apple up and down. In the long run, the conservation of the up and down energy loss translates to the availability of extra energy to improve speed and performance.

Implications

The foregoing discussion focuses on tether-supported arms' efficiency gains and energy savings. If the tethers were used to increase arm-swing frequency without any stride adjustments, clearly speed and performance will improve, but at a cost of greater energy expenditure. In reality, results from using the tether support will fall somewhere between these two extremes, with a combination of more steps taken and a reduction in stride length, which together yield an improvement in overall results.

For the super runners, the reduction of stride length is already discussed as a decrease in air distance, which equates to a lower maximum leg force with each stride. For the ordinary runner, maximum leg force is reduced due to a smaller leg angle. Thus the feeling of the tether support would be somewhat like that of a cyclist selecting a lower and easier gear.

Another Word Related to Race Walkers

It was mentioned earlier that race walkers have gained natural frequency improvement with some success. Observing race walkers in motion, it should be obvious that they swing their arms with a punching motion to keep their lower arms about horizontal with the ground; thus rotational inertia of the lower arm is eliminated/reduced by active elbow angle adjustment. However, the process has its limitations. First, it takes skills and practice to master the walker arm-swing movement, and second, the resting center position still has the elbow pointed back, which limits the amount of natural pendulum movement as previously discussed for the bent running arm configuration. Thus with walkers going for maximum stride ground distance, the large angular momentum from the resulting large leg swing is offset by twisting the upper body and swinging the arms out in front beyond the point of pendulum gravitational potential energy recapture, like with the hand weights. Of course, body twist does not provide any energy recapture at all. The process is not perfect, but it allows race walkers to maximize speed otherwise not achievable without well-trained arm swing motion.

With that said, it should be obvious that race walkers would most easily adjust to using the tether support to improve performance, with benefits not achievable from traditional walker arm swing motion.

A Final Word on Physics

With gravitational force a constant, the up and down bouncing velocity is proportional to time, and vertical displacement is proportion to time squared. Meanwhile, work is the product of force and distance. With the exponential relationship between distance and time, the work done and lost associated with one bounce of a given duration of time is twice the total loss from two bounces of half the duration each, although total air time is the same in both cases.

For the Olympic/elite runners, not only are the air distances reduced as established earlier, each bounce is now shorter in duration to further benefit from the exponential effect on the work necessarily expended to achieve gliding through the air and is lost in the process.

For the ordinary runners who always have at least one foot on the ground, the shorter time associated with each step imposes a lower cap on the maximum fathom bounce that could possibly occur, and the runners benefit equally from the ancillary exponential effect on work done and wasted.